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FINAL TECHNICAL REPORT ON NASA JPL CONTRACT "STARBURSTS AND NUCLEAR ACTIVITY IN SEYFERT GALAXIES" (JPL CONTRACT 958008, U.MD. FAS 01-4-33194)

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1) IRAS Spectra

In an attempt to clarify the mechanisms behind the Seyfert far infrared (FIR) emission, we have used the IRAS data base as a means for delineating the presence of starburst, AGN and/or cirrus infrared components in Seyfert galaxies. To this end, we have studied a matched sample of Seyfert and normal galaxies via the IRAS data.

The sample set is composed of 42 Seyfert galaxies from the **Revised Shapley-Ames Catalog** (hereafter RSA, Sandage and Tammann, 1981) and 42 comparable RSA non-Seyfert control galaxies (Heckman, et al. 1989). The RSA control sample, consisting of normal spiral galaxies, was selected to match the RSA Seyfert sample according to Hubble type, absolute magnitude and distance. Seventeen additional Seyferts, many with known star formation activity, complete the sample set.

IRAS fluxes o flux limits in Janskys at 12, 25, 60 and 100 μ were obtained for 98 of the sample galaxies. To facilitate examination for spatially extended sources and utilize the increased sensitivity of coadded observations, fluxes were chosen from ADSCAN/Scanpi output calculated at the Infrared Processing and Analysis Center (IPAC) in Pasadena, rather than from the IRAS Point Source Catalog. For sources appearing as detections only, without reliable flux measurements (signal to noise ratio less than five), five sigma was used as an upper limit. All values from the Scanpi photometry have been calibrated with respect to the Point Source Catalog.

ADSCAN/Scanpi output provides peak and integrated fluxes for each of four coadditions (two averages, median and weighted mean), plus the peak flux of a point source template fitted to the data. Of the four coadded scans, the weighted mean, which reduces the importance of noisy data, proved to be the most useful. Good point sources were well represented by peak and integrated fluxes, whereas the peak flux was an insufficient value for extended source fluxes.

Identifying spatially extended sources was possible by examination of the measured full width at half maximum of the source emission. Point source widths fall near the template widths (0.76, 0.77, 1.378 and 2.986 arcm in at 12, 25, 60 and 100 μ, respectively; Fullmer and Helou, 1987), whereas spatially extended sources have larger widths. Extended objects were also visually identifiable using the coadded emission plots provided with ADSCAN/Scanpi out-put. In addition, templates calculated for extended sources do not provide a good match to the data, whereas there is a strong correspondence between calculated templates and point source emission.

A convenient representation of IRAS data is the color-color diagram. Spectral indices for each object to be plotted ont he color-color diagram were calculated from the IRAS fluxes, where objects are categorized according to the relative "steepness" or "flatness" of their spectra in the specified wavelength range. Though the intrinsic scatter of the color-color diagrams is large, these diagrams can be divided into regions of activity. Regions have been identified with a nuclear "powerlaw" component likely to be nonthermal nuclear radiation, with hot dust heated by a nuclear powerlaw, with a relatively warm thermal component probably due to starburst activity, and with the relatively cool emission from the galaxy disk.

Following the method of Rowan-Robinson (1987), identification of regions of activity on the color-color diagrams has been complimented by a quantitative decomposition of the IRAS emission into three parts. As in the color-color diagram, these components are described as follows: 1) the normal disk component, regarded as thermal re-radiation from dust grains heated by diffuse starlight -- cirrus, 2) a starburst component modeled as hot stars in an optically thick dust cloud, and 3) an AGN or "Seyfert" component estimated as the emission from a central, power-law continuum source or from dust surrounding and heated by this source. Using a matrix inversion method on each galaxy, we have thus derived the fraction of flux in each band which is provided by each of these three components. Because of the intrinsic scatter in the spectral properties of each component, this method has shown itself to be a convenient parameterization of the data set as a whole, rather than a specific description for each object:

Results using the color-color diagrams have shown the expected, systematic differentiation between spectral indices of Seyferts and controls, with a clustering of control galaxies in the "cirrus" regions of the diagrams, indicating that the infrared emission of these objects is dominated by cirrus in galaxy disks. For the Seyferts, there is a wide range in the fractions contributed by each of the three model components. It is encouraging that the Seyferts found to be spatially extended in the IRAS observations are always dominated by the cirrus component, as derived from the spectral decomposition. Other correlations were also found. This work formed the "second year project" of Heidi Kirkpatrick (1989) and a first draft of a paper for publication has been prepared.

2) Correlations With Other Wavebands

For a more complete understanding of the emission from Seyfert galaxies, it is necessary to study them over a wider spectral range. To this end, we have compared the results from the decomposition of the IRAS data into three model components with existing VLA data on the diffuse (starburst) radio-continuum component, with the mm-wave CO emission from Seyferts, and with narrow band optical images using well-established line-ratio diagnostics to separate starburst and central nonthermal components in the ionized gas.

In a recent paper (Heckman et al. 1989), we have compared the IRAS data for Seyferts and a comparison sample with their CO J = 1-0 emission line properties. The 55 Seyfert galaxies with CO data--as a class--follow the same relationship between CO and far-IR luminosities as do normal and starburst galaxies, suggesting that the far-IR radiation in this sample of Seyferts has the same origin as in normal and starburst galaxies (dust reradiation of starlight). We have then compared the far-infrared luminosities of all the 42 known Seyfert galaxies in the RSA to those of a sample of non-Seyfert galaxies from the RSA, carefully chosen to match the Seyferts in absolute magnitude, distance, and Hubble type. The RSA type 2 Seyferts have an average far-infrared luminosity that is ~4 times larger than the non-Seyfert comparison sample, while the RSA type 1 Seyferts are not significantly more luminous than the non-Seyferts. Thus, type 2 Seyferts may have abnormally large dust and molecular gas contents and high rates of star-formation, while the Seyfert 1 galaxies appear normal. This molecular gas may be related in some indirect way to the nuclear material hypothesized to obscure the broad line region in type 2 Seyferts. The differences in CO and far-IR properties also imply that the two classes of Seyfert galaxies are intrinsically different from one another and that the Seyfert 1 population cannot evolve into the Seyfert 2 population in a time scale less than a few million years (or vice versa). We have also searched for any very broad CO emission lines associated with the high-velocity optical emission-line gas in six Seyfert nuclei. We have been able to put limits on this component that are in some cases a small fraction of the narrower CO emission detected from the galaxy. We find that while Seyfert galaxies exhibit a statistically significant correlation between CO luminosity and nonthermal radio power, they are sytematically stronger nonthermal radio sources than non-Seyfert galaxies having the same CO luminosity. We argue that these results support the idea that the radio continuum in Seyferts has a composite origin with both starburst and active galactic nucleus components. We have also compared the CO line widths to the widths of the global H I λ = 21 cm lines, the nuclear [OIII]λ5007 lines, and the central stellar velocity dispersions. The CO line widths correlate best with the HI line widths, and the correlation between the CO and [OIII] widths improves markedly when the CO (but not the [OIII]) line widths are corrected for galaxy inclination. This suggests that the CO is coplanar with the galaxy disk (like the HI), but that the nuclear [OIII]-emitting region (the classical narrow line region) is not. The CO versus [OIII] line width correlation provides additional evidence for a gravitational component to the dynamics of the narrow line region.

A study of Seyfert galaxies with clear observational characteristics of circumnuclear star formation was published

(Wilson 1988). These characteristics include extranuclear, low excitation, narrow, optical emission lines from HII regions, "diffuse", nonthermal radio emission (apparently from multiple supernova remnants), mid infrared emission features of heated dust, and very steep infrared spectra between 25 and 60 μm. For Seyfert galaxies dominated by such "diffuse" radio emission, the correlation between 1.4 GHz and 60 μm fluxes is in excellent agreement with that found for other extragalactic star forming regions. The far infrared radiation observed by IRAS from these galaxies is predominantly thermal emission from dust heated by hot stars. On the other hand, Seyfert galaxies with radio emission dominated by "linear" (double, triple or jet-like) structures tend to have relatively flat 25-100 μm spectra, and the ratio of their 1.4 GHz to 60 μm flux densities is considerably higher than that for star forming regions. The radio and far infrared emissions from this class appear to be dominated by the Seyfert nucleus, with the far infrared originating directly from a nonthermal source or from dust heated by one. The infrared emission observed by IRAS from Seyfert galaxies represents, in general, a mixture of nuclear, galaxy disk and starburst components, with the relative proportions varying from galaxy to galaxy.

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